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TITLE OF THE INVENTION (230 characters max)

ADAPTIVE ANTENNA ARRAY CALIBRATION SYSTEM AND METHOD

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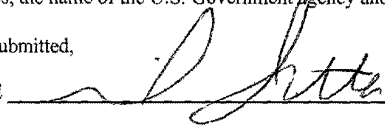
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Respectfully submitted,

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BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to the field of RF communication systems, and more particularly to a system and method for calibration of adaptive antenna arrays.

Description of the Related Art

In order to remain competitive in an increasingly crowded market, wireless equipment manufacturers experience constant pressure to reduce their costs and improve performance. One way to reduce the overall cost of a cellular phone system is to re-design individual system components or software so that the system may operate more efficiently. For example, it would be desirable to supply more users while maintaining an acceptable signal quality. One method for increasing the efficiency and performance of a cellular system is through the use of adaptive antenna arrays ("adaptive arrays"). Until recently, adaptive arrays had been used almost exclusively for military anti-jam applications. Non military uses were limited by losses and signal degradation resulting from the combining of a large number of analog signals (in transmit mode) and splitting the large number of analog signals (in receive mode) required in multi-channel communication systems. The losses and degradation noted was generally more than offset by any advantage gained through employing an adaptive antenna array. With the advent of high speed digital signal processing, losses and signal degradation associated with analog processing to accomplish the same result are almost entirely avoided.

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Adaptive antenna array systems provide greater range over traditional technologies due to increased antenna gain. As a carrier wave propagates through space, the signal power decreases. Since mobile subscribers cannot detect signals below a minimum threshold level of transmitted power, increasing antenna gain extends the distance a carrier wave can travel. Thus, an adaptive antenna array can increase the cell size that a given BTS can serve.

An adaptive antenna array can also increase user capacity over traditional antenna technology by amplifying the signal coming from and going to the mobile user while dampening other signals coming from other directions. This ability is commonly referred to as "digital beamforming." By steering a beam and positioning multiple nulls, an adaptive array is able to reduce co-channel and adjacent channel interference. This allows each cell to use all frequencies within an operator's licensed band and may make it possible to use single frequencies more than once within a given cell. Separating multiple signals having the same frequency is possible using an adaptive array, provided the signals arrive from angles or otherwise have distinctive propagation paths. In the same manner, echos caused by multipath arrivals of a desired signal can be detected and suppressed.

An antenna array consists of N identical antenna elements arranged in a particular geometry. The geometry of the array determines the amount of coverage in a given spatial region. A very commonly used array type is the uniform linear array.

For any given geometry, the phases and amplitudes of the currents exciting the array elements determine the gain of the array in a certain direction. The phases and

amplitudes of the currents on the antenna array elements can be electronically adjusted such that received signals from a certain direction add in phase, and maximum gain is achieved in that direction. Due to the reciprocal nature of antennas, this approach is also generally applicable to focus the array beam for transmission as well, assuming the transmit and receive frequencies are equal or nearly equal.

To adjust the amplitude and phases of the individual array currents, complex weights are placed in the signal path of each antenna element. The weighted signals are combined and the output is fed to a control unit that operates on the individual signals and their combined output to update the weights. Weight updating is usually accomplished adaptively to satisfy a chosen optimization system.

There are several commonly used adaptive algorithms available for updating the weights. These include gradient based algorithms, recursive methods, and others such as the constant modulus method (CMA).

For the phases and amplitudes of the various currents on the antenna array elements to be controlled, the individual (unweighted) array currents must arrive at the same instant and with the same amplitude. Consequently, the relative phase and amplitude offsets for each of the complete transmit and receive paths associated with each array element must be determined to enable proper determination of a signal's angle of arrival as well as for precise beam steering. In digital systems, the complete transmit and receive paths extend between the respective digital signal processors and the respective antenna elements.

Each adaptive array antenna element requires a separate transceiver chain for

operation of the adaptive array. Thus, each antenna element is provided a dedicated receiver apparatus chain and transmit apparatus chain. For example, a receive apparatus chain may include an antenna element, cables, filters, RF electronics, physical connections, and an analog-to-digital converter, assuming the processing is digital. Due to normal manufacturing variances in the manufacture of the antenna array elements, connecting cables, and transmit and receive electronics chains, there will be differing errors and non-linearities introduced by signal paths comprising combination of these components. Thus, identical signals passing through the different elements of antenna array will emerge with different amplitudes and phases.

Similarly, identical signals passing through different cables and electronics will result in distinct resulting amplitude and phase. These composite amplitude and phase errors in a given antenna signal path can be captured for a fixed reference angle (for example, north) and a set of receive and transmit calibration factors calculated to equalize the transfer functions of the various receive and transmit apparatus chains. Each antenna array element along with its corresponding cables and the corresponding receive electronics in the path from each antenna element to its respective digital signal processor shall be referred to as the "receive apparatus chain" for each antenna element. Similarly, each antenna array element along with its corresponding cables and the corresponding transmit electronics from the respective digital signal processor to the respective antenna element shall be referred to as the "transmit apparatus chain" for each antenna element. These calibration factors can be used to transmute the actual signals that are actually seen at the end of each antenna array element chain

into corresponding signals that would be expected at the end of each chain if all signal path components behaved identically.

Because the transmit signals and the receive signals follow somewhat different hardware paths, the adaptive antenna system will have both transmit and a receive calibration factors. It should also be noted that the phase and amplitude shifts that occur in the receive and transmit apparatus chains are, in general, frequency dependent. Thus, in broadband applications, calibration factors must generally be determined at the plurality of carrier frequencies used.

Accurate real-time calibration is required for all receive and transmit apparatus chains. Periodically, the calibration procedure must be performed as differences in the propagation path may vary during the day and from day to day due to temperature and other environmental conditions. Since there are active components involved their responses will change with time and temperature. Thus, for an adaptive antenna array to function properly, frequent calibration of the various transmit and receive apparatus chains should be performed.

The complete paths for the receive apparatus chains are relatively easy to calibrate since a fixed near-field or far field transmitter can be used as a calibration source to allow the respective receive apparatus chain path delays and magnitude shifts to be calculated and stored. Unfortunately, the calibration of the transmit apparatus chain path delays and magnitude shifts are much more difficult because a single external transmitter cannot be used as a calibration reference. As a result, transmit apparatus chain calibration is generally performed with costly dedicated

hardware including near and/or far-field transmit sources or receivers.

Therefore, there is a need for a method to calibrate all transmit apparatus chains and receive apparatus chains without the addition of dedicated calibration hardware such as near and/or far-field transmit sources or receivers. Moreover, such a method should preferably not impact a cellular system's traffic capacity.

BRIEF DESCRIPTION OF THE DRAWINGS

There are presently shown in the drawings embodiments which are presently preferred, it being understood, however, that the invention is not limited to the precise arrangements and instrumentalities shown.

Fig. 1 shows a simplified block diagram of a wideband digital beamforming base station transceiver (BTS).

Fig. 1 shows a simplified block diagram of a wideband digital beamforming base station transceiver (BTS).

DETAILED DESCRIPTION OF THE INVENTION

Referring to FIG. 1, a simplified block diagram of a digital beamforming base transceiver station (BTS) is shown. BTS 200 shown includes a 4 element antenna array 210-213 (hereafter 210).

Each antenna element has a dedicated receive apparatus chain comprising filter/duplexer 220-223 (hereafter 220), broadband digital transceiver 240-243 (hereafter 240), channelizer/combiner (XMUX) 250-253 and associated connectors inclusive of digital signal processor boards 270-273 hereafter 270). In the receive mode, XMUX 250 operates as a channelizer. In a broadband application, digital signal processor boards comprise a plurality of individual digital signal processors. Filter/duplexer 220 performs amplification, filtering and down conversion to IF of received signals. In broadband applications, assuming multiple frequency channels are active at any given instant, received signals are multi-channel signals.

The broadband digital transceiver 240 performs A/D conversion then digitally down-converts the received signal. The multi-channel digital signal output by the broadband digital transceiver 240 is separated by channelizer 250 into baseband digital signals having an I and Q representation for each active channel. There is one channelizer 250 provided for each antenna element 210. In the preferred embodiment, the channelizer 250 is a FFT channelizer. The baseband digital signals, respectively associated with each antenna element 210, are then communicated to a digital array processor 260. Although shown as a separate module and positioned on the channelizer/combiner 250 side of control and timing bus 262 and switching bus 264,

digital array processor 260 can be positioned on the opposite side of buses 262 and 264. Moreover, in the preferred embodiment, digital array processor 260 can be positioned on the same board as digital signal processor 270, digital signal processor 270 being on the side of buses 262, 264 opposite to XMUX 250.

Digital array processor 260 may be used to store the various calibration factors and angular weighting factors. Calibration factors and angular weighting factors are preferably stored separately. Calibration factors are used to compensate for relative path phase delay and amplitude variations that occur when signals traverse the various transmit and receive apparatus chains, with reference to a fixed reference angle (for example, north). The angular weighting factors are used to point the antenna beam and nulls into the desired directions (for both transmit and receive) relative to the reference angle (for example, +23 degrees north). The phases and amplitudes of the calibration factors and angular weighting factors are effectively added together to result in a net weighting factor that is applied to signals traveling in each antenna apparatus chain for each signal frequency and time slot (in TDM systems).

Digital array processor 260 may be used to calculate the various calibration factors and angular weighting factors and store these factors. Through application of net weighting factors to each of the applicable apparatus chains, digital array processor 260 can adjust the baseband digital signals received from and for transmission by each antenna element 210 to beamform each active channel. The net weighting factors can be resolved and applied using the recently available "Super DSP" cards, where one processor does the beamforming for a single RF carrier (all 8 time slots in GSM, for

example) and a second processor does the signal processing (modem functions). Having both processors on the same board reduces signal interconnectivity requirements and improves system reliability. Combining the processors on a single board also generally reduces system cost compared to separate board implementations when implementing adaptive antennas.

For the receive path, the respective phase and amplitude net weighting factors are preferably applied after the XMUX 250 (digital channelizer) and before the DSP 270. DSP 270 receives the signal components adjusted with respective net weighting factors from each receive apparatus chain output by the digital array processor 260 and demodulates these signals to recover the combined beamformed communication signal. The recovered communication signal is then communicated to the communication system via a suitable interface (not shown).

System operation in the transmit direction is quite similar to the receive direction. Each antenna element has a dedicated transmit apparatus chain comprising filter/duplexer 220, multi-carrier power amplifier (MCPA) 230-233 (hereafter 230), broadband digital transceiver 240-243, channelizer/combiner 250-253 (XMUX 250) using the combiner and associated connectors inclusive of respective digital signal processors 270. Digital signal processors 270, are associated with a specific antenna element 210 and a specific frequency channel for processing respective ones of a plurality of incoming (voice/data) communication signals to be transmitted over respective frequency channels. Their processed (modulated and encoded) outputs are supplied to the digital array processor 260, which can apply appropriate net weighting

factors to each active channel and for each transmit apparatus chain associated with each antenna element 210. For the transmit path, the phase and amplitude net weighting factors are preferably applied after the DSP 270 (modulation) and before the XMUX 250 (digital combiner). At these points in the signal path, each signal (RF frequency and time slot) is a baseband signal having an I and Q representation.

The outputs of the digital array processor 260 for each transmit apparatus chain are input into respective combiner 250. In the preferred embodiment, there is one combiner 250 for each antenna element 210 and the combiner is an inverse FFT combiner. The FFT combiner 250 forms a multichannel digital signal which is input to the broadband digital transceiver 240, where it is upconverted to IF, D/A converted, and amplified by a high power multi-carrier power amplifier (MCPA) 230. The composite multi-frequency signal is then supplied to RF elements 220 for amplification, filtering and up conversion from IF to RF. The antenna elements 210 then each transmit the beamformed multi-frequency communication signal.

Although a 4 element antenna array embodiment is shown in Fig. 1, the invention is not limited to 4 antenna elements. Note that although four DSP boards 270 are shown in Fig. 1, each may provide a plurality of digital signal processors per board. For example, 24 digital signal processors may be provided per DSP board 270. In the preferred embodiment of the invention, 96 channels are supported by BTS 200 through use of 12 RF carriers and 8 TDM time slots. A separate digital signal processors may be dedicated to each channel (timeslot), or a digital signal processor having sufficient processing speed may process multiple channels, such as all eight channels (timeslots)

in GSM systems.

To obtain the full advantages of an adaptive antenna array, both transmitted and received signals must be calibrated so that unweighted signals traveling along the various antenna apparatus chains from respective DSPs 270 to antenna element 210 each reach each antenna element 210 simultaneously and with the same amplitude. Preferably, the various transmit and receive apparatus chains are calibrated to all be within 1 to 2 degrees of phase and 0.1db to 0.2 db in magnitude relative to each other. Similarly, all received signals by each antenna element 210 should reach their respective DSP 270 nearly simultaneously and with the nearly the same amplitude as well. Consequently, accurate determination of receive apparatus chain calibration factors and transmit apparatus chain calibration factors to and from each antenna element 210 to respective DSP 270s are generally required to implement beamforming.

At the time of system installation, the physical distances between the various antenna elements are measured and recorded. This information is used to calculate and compensate for free space path time delays between the various antenna elements. For example, for a triangular 4 element system where a single antenna is placed in the center of the triangle, there are 4 unique distances to measure.

In one aspect of the invention, calibrating factors for the various receive and transmit apparatus chains are determined through use of a remote device to receive, frequency shift and loopback signals transmitted by BTS 200. In the preferred embodiment, a remote wireless translating repeater ("translating repeater") may be used as the remote device for calibration of an adaptive antenna array included in BTS

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200. Translating repeaters may already be installed in conjunction with BTS 200 in certain cellular systems. In this case, the translating repeaters result in no added system expense. If a wireless translating repeater is not already used in the cellular system, a reduced cost modified translating repeater version can be used, the modified translating repeater having only backhaul receive and transmit functions.

The method requires the total delay and magnitude shift (collectively the "signal shift") for a round trip (TD) of a loopback signal transmitted and received by BTS 200 to be measured. Round trip signal shifts between transmitting and receiving antenna apparatus chains consist of the following components:

1. signal shift from the respective DSP 270 to respective transmit antenna element 210 (transmit apparatus chain), referred to as TX1- TXn; plus
2. delay during signal travel in free space to the remote device, referred to as D1-Dn; plus
3. signal shift during remote device signal processing; plus
4. delay during signal travel in free space from remote device back to respective antenna elements, referred to as D'1 – D'n (note that due to symmetry $D_1=D'1$; $D_n=D'n$), plus
5. Signal shift from each receiving antenna 210 to their respective DSP 270 (receive apparatus chain), referred to as RX1-RXn.

For a 4 element antenna array, 16 distinct round trip signal shifts can be measured, 4 per antenna element. The translating repeater location is measured and

characterized with reference to the angular position and distance between the

translating repeater and the various BTS antenna elements 210. This is normally accomplished using a survey. This information is then stored and taken into account during calibration factor calculations to account for the differences in free space delays between the remote device, such as a translating repeater, and the various antenna elements.

Method and Apparatus Employing a Remote Wireless Repeater For Calibration of a Wireless Base Station Uplink and Downlink Adaptive Antenna Array

To initiate a first calibration process, a remotely positioned translating repeater is signaled by BTS 200 to enter a loopback mode by an appropriate signal. The translating repeater may be placed in the loopback mode for one frame (8 time slots in GSM). Once in the loopback mode, signals received by the translating repeater are coupled off to a low level (e.g. -40 dB), additionally attenuated frequency shifted from the transmit to receive band (for example, 80 MHZ lower for GSM-1900) and re-transmitted back to the BTS.

The BTS 200 transmits a loopback signal, such as a GSM access burst, from each antenna element, one at a time. The translating repeater receives and re-transmits loopback signals which are received by all antenna elements of the BTS adaptive array. Signal shifts for each receive apparatus chain may be measured and calibration factors determined from resulting receive apparatus chain signal shifts measured from receipt of any one of the returned loopback signals originally

transmitted by BTS from any antenna element. These values may be recorded for

each antenna receive chain to permit computation of calibration factors for the respective receive apparatus chains to compensate for receive signal shift differences.

Similarly, round trip signal shifts can be measured. By using measured round trip signal shift data for signals transmitted and received by each antenna element and subtracting the earlier determined respective receive signal shifts and adjusting for free space delay differences, transmit apparatus chain calibration factors can be determined. These factors can be used to compensate for transmit signal shift differences from signals transmitted by each antenna element. Since signal shifts are frequency dependent, the calibration process for both transmit and receive apparatus chains are generally repeated for all carrier frequencies supported by BTS 200.

Once the receive and transmit chain calibration factors are calculated and stored by the BTS, the angle of arrival for each uplink channel may be calculated and stored. In practice, angle of arrival for translating repeater transmissions relative to the BTS is known (e.g., based on a survey) at the time of installation and does not change over time. Thus, the translating repeater angle of arrival can be used as an absolute reference, permitting mobile user angle of arrivals at the BTS 200 to be made relative to that fixed reference angle.

In a multi-carrier BTS utilizing 12 RF carriers and 8 TDMA time slots, 96 full duplex channels of GSM are available. In this configuration, 96X2 values of calibration factors are stored for each antenna element and its dedicated receive apparatus chain.

Thus, for a duplexed system having 96 channels and 4 antennas, 768 calibration factors are stored to support beamforming in the receive direction. After the uplink

angle of arrival is determined, the downlink steering angle is determined as the reciprocal direction.

In actual operation, the BTS 200 uses the receive chain apparatus calibration factors when an uplink signal is received by antenna elements 210 to determine the angular location of the signal source, such as a mobile user. Various algorithms known in the art permit accurate identification of the mobile's location, allowing the determination of the angle of arrival of the mobile user's signal. Upon receipt of the arriving signal, the digital array processor 260 may be used to determine the angle of arrival of the incoming signal by measuring the signal shifts of the arriving signal after traveling the respective receive apparatus chains of the several antenna elements 210. In this determination, receive apparatus chain calibration factors already determined and stored therein are used to compensate for differences in the various receive apparatus chains.

Using the mobile user's angle of arrival, angular weighting factors can be readily calculated using methods known in the art to narrow the beam to focus to the user's location and to position nulls to steer toward interference sources. Angular weighting factors are combined with respective calibration factors to produce appropriate net weighting factors for application to the signal paths of each receive antenna chain. Appropriate net weighting factors permit pointing a beam towards the mobile user and up to $N-1$ nulls (N is the number of antenna elements) toward interference sources. Similarly, using the inverse of the angle of arrival for transmitted signals, respective transmit apparatus chain net weighting factors are determined to point a beam towards

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the mobile user and up to N-1 nulls toward interference sources.

Translating repeaters may be used to calibrate the antenna array in either a passive analog loopback repeat function or an active receive/demodulate remodulate/transmit function. In the passive repeat function, downlink signal are simply frequency translated and looped back to the BTS 200. In the active receive function, the translating repeater can demodulate the received signal and remodulate (and frequency shift) the received signal for retransmission. The active receive function can be used to send additional information such as RSSI (receive signal strength) of the mobile user to the BTS during calibration.

Transmit calibration factors are preferably constantly updated during system operation because of component drift, principally due to environmental factors. For example, the length of RF cables and jumpers change (and result in corresponding shifts in time delays to traverse) with heating and cooling from the sun, day/night, weather and other environmental factors. Devices such as surface acoustic wave (SAW) filters found in both the BTS upconverter (downlink transmit) and BTS downconverter (uplink receive) as part of broadband digital transceiver 240 circuitry are particularly sensitive to temperature and are known to produce significant changes in signal shift from modest changes in temperature.

Channelizer 250 separates the inputted composite digital signal comprised of all active RF carriers into separate digital signals representing each RF carrier from a composite signal. Using the angle of arrival data determined for mobile users for all active timeslots for each RF carrier in a TDM system, net weighting factors may be

determined by the digital array processor 260 and be separately applied to each active timeslot to point a beam towards the mobile user's location and to point one or more nulls at the most intense interference sources.

Turning to the transmit direction, signals output by DSP 270 to the digital array processor 260 are separate digital signals for each active channel (timeslot). Using the reciprocal of the angle of arrival for the received signal, the digital array processor 260 calculates the optimum net weighting factors for the various transmit apparatus chains and places these net weighting factors in each of the channel's transmit signal path at the digital array processor 260 to point the transmitted antenna beam and one or more nulls in the reciprocal of the uplink signal direction.

Assuming full channel use, the digital array processor 260 generally determines optimum net weighting factors for each antenna element 210 for each of the 96 full duplex signals. However, it is often not desirable to beamform the dedicated control channel used as beacons, since such control channels must be generally available throughout a given cell. Consequently, in the absence of major blocking structures, no weighting factors will be applied to BTS 200 transmitted control channels which function as beacons.

Calibration factors and angular weighting factors may be stored in memory locations in the base station digital array processing card 260. These factors are preferably stored separately. Neglecting control channels, for a cellular system having 96 channels and having 4 duplexed transmit/receive antennas elements, the number of memory locations required is 768 ($96 \times 2 \times 4$) for calibration factors and the same number

for separately stored weighting factors. Angular weighting factors must generally be frequently updated since the cellular user may be moving and a variety of interference sources may arise.

Calibration of a Frequency Division Duplex (FDD) Wireless Adaptive Array Using a Remote Translating Repeater

In another calibration method, a translating repeater is placed (or if already used in the cellular system, utilized) at a known location with respect to BTS 200. If not already known, the translating repeater location is measured and characterized with reference to the angular position and distance between the translating repeater and the various BTS antenna elements 210. To initiate of the calibration process, the translating repeater is signaled by the BTS to enter a loopback mode. In the loopback mode, received signals are frequency shifted by the translating repeater and then redirected back to the BTS.

Different signals (e.g. tones) are transmitted simultaneously by BTS 200 from each antenna element 210 of the antenna array. Each signal transmitted has a known phase and amplitude. All transmitted signals share the same RF carrier frequency.

All signals transmitted from each antenna element are received by the translating repeater. In the loopback mode, the translating repeater mixes the individual signals containing the individual tones to form a composite signal containing all the tones. The composite signal is frequency translated to a frequency within the receive frequency band of the cellular system.

The single frequency shifted composite signal containing all the tones is transmitted by the translating repeater and received by the adaptive antenna array. The composite signal received by each antenna element travels through each antenna element's receive apparatus chain. The composite signal's amplitude and phase characteristics received at each of its antenna elements and propagated through respective receiver apparatus chains is then measured at the antenna element's respective DSP 270. Free space path differences between the translating repeater and various antenna elements are considered in the calculation. Factoring in free space path differences, measured signal shifts of the composite signal for each antenna receive apparatus chain are measured by DSP 270 and compared to other receive apparatus chain signal shifts. Relative signal shift values between each antenna receive apparatus chain adjusted for free space path differences between the translating repeater and the various antenna elements allows the determination of calibration factors which enable the BTS 200 to compensate for variations between the uplink path transfer function for each receive apparatus chain.

The BTS 200 may also determine calibration factors for each transmit apparatus chain using this method. DSP 270 may be used to separate the composite signal having the plurality of tones received at any one of the antenna elements 210 into the plurality of frequency shifted individual signals having single tones which were originally transmitted by each of the antenna elements. Each of the received tones constituting the composite signal travels the same receive apparatus chain, from any selected antenna element to its respective DSP 270. Comparing the relative phase and

amplitude of each originally transmitted signal to the amplitude and phase of the corresponding received signal and adjusting for free space path differences between the translating repeater and the various antenna elements 210, calibration factors may be determined for each antenna transmit apparatus chain. These transmit apparatus chain calibration factors can be used to compensate for differences in the downlink path transfer function for each of the transmit apparatus chains.

Multifrequency Farfield Calibration of a Frequency Division Duplex (FDD)

Wireless Adaptive Antenna Array Broadband Base Station Using a Remote Wireless Repeater

In a related method using a translating repeater, calibration factors may be determined over a range of frequencies using a farfield calibration method. At any given time, the transfer characteristics of the various transmit apparatus and receive apparatus chains can vary over the frequency band of broadband BTS 200. This is primarily due to the differences in the broadband transceiver's 240 SAW filter transfer characteristics from its band edges to the center of the filter's band. Frequency dependence of the calibration factors requires the various antenna paths to be analyzed at several frequencies across the broadband BTS frequency band.

This invention uses a translating repeater with loopback capabilities as part of the calibration process. The repeater is placed at (or utilized from) a known location with respect to a BTS having an adaptive antenna array. The BTS and translating repeater can each be programmed with a set of calibration frequencies.

To initiate the calibration process, the translating repeater is signaled to enter a loopback mode. The BTS transmits differing calibration signals (e.g. tones) from each of its antenna elements, all at a first carrier frequency. A composite calibration signal having the plurality of tones is received by the translating repeater and looped back (frequency shifted) to the BTS. Receive apparatus chain calibration factors are determined after adjustment for free space path differences from the relative amplitude and phase of the composite calibration signal at DSP 270 received by each of the receive apparatus chains. As before, transmit chain calibration factors for each transmit apparatus chain can be determined (after adjustment for free space path differences) by receiving the composite calibration signal at any antenna element and using DSP 270 to split the received composite signal into its component calibration signals.

BTS 200 next signals the translating repeater to step to the next programmed calibration frequency. Likewise, the BTS 200 steps to the next calibration frequency and the calibration process is repeated at a second carrier frequency. Calibration information is saved for each carrier frequency and is used to compensate for the differences in the transfer function of the various receive apparatus chains and transmit apparatus chains when a call is assigned having a given carrier frequency.

Nearfield Calibration of a Frequency Division Duplex (FDD) Wireless Adaptive

Array Using a Mixing Tone and Calibration Receiver

In another calibration method, a frequency division duplex (FDD) wireless adaptive antenna array base transceiver station (BTS) may be nearfield calibrated by

transmitting a mixing tone and using a special frequency translating receiver device.

The frequency translating receiver device may be mounted on the tower top supporting the BTS adaptive array elements, near the adaptive array elements. Upon installation, the respective distances between the frequency translating receiver device antenna and the various antenna elements are measured and stored.

A mixing tone is generated by any of BTS transceivers 240. The mixing tone can be transmitted isotropically. The same antenna element may be used to transmit the mixing tone as for the frequency translating receiver device. The frequency of the mixing tone is set to approximately equal to the frequency offset of the wireless FDD communication system. For example, the uplink and downlink frequencies for PCS-1900 is exactly 80MHz. Therefore, the frequency of the mixing tone used would be 80 MHz.

A calibration signal is transmitted at one of the FDD system's downlink frequencies from each of the adaptive antenna elements/transmit chains (one at a time). The calibration signals are mixed with the mixing tone at the frequency translating receiver device. The frequency translating receiver device includes a local oscillator for mixing. The mixing process generates an intermodulation product at the receive frequency which may be separated from other intermodulation products by a suitable filter. The desired intermodulation product is the addition product of the transmit band calibration signal and the mixing tone.

A first calibration signal is transmitted from a first antenna element at the FDD systems downlink frequency at a first time along with the mixing tone. The mixing tone

can be generated by any of BTS 200 transceivers 240 and transmitted from any antenna element. The amplitude and phase characteristics of the uplink frequency intermodulation product formed by the frequency translating receiver device from the calibration signal transmitted at the first time is received by BTS 200 at each antenna element and measured by DSP 270. Adjusting for free space path differences between the frequency translating receiver device antenna and the various BTS antenna elements 210, respective receive apparatus chain signal shifts are easily determined. Differences in receive apparatus chain signal shifts can be used to calculate calibration factors to compensate for the differences in the receive apparatus chain propagation paths for each of the antenna receive apparatus chains.

Similarly, at later instants, FDD downlink calibration signals are transmitted, one at a time, from each of the other antenna elements. After mixing the calibration signal with the mixing tone, the resulting receive band intermodulation products are received by each BTS antenna element 210. For a 4 element antenna array, 16 round trip signal shifts can be measured, 4 per antenna element. Round trip signal shifts are then adjusted for free space path length differences between the frequency translating receiver device antenna and the respective antenna array antennas. Sixteen independent equations result with four unknown transmit signal shifts from respective DSP 270 to respective transmit antenna element 210 (transmit apparatus chain) permit solution of the various transmit signal shifts and determination of transmit calibration factors. Once the transmit and receive calibration factors are determined, the calibration factors can be loaded into digital array processor 260.

Multifrequency Farfield Calibration of a Frequency Division Duplex (FDD)

Wireless Adaptive Antenna Array Broadband Base Station Using Remote Wireless

Repeaters

In another calibration method using translating repeaters with loopback, multiple translating repeaters are used. In situations where the translating repeaters operating frequencies cannot be remotely changed, it may be advantageous to use multiple translating repeaters, each translating repeater set to operate at different frequencies to support calibration over multiple frequencies.

Each translating repeater may be configured to different calibration frequencies across the frequency band allocated to the broadband BTS. These translating repeaters can be placed in positions such that they may be used to calibrate multiple base stations. To initiate the calibration process, a first translating repeater is signaled to enter a loopback mode by a BTS. The BTS transmits differing calibration signals (e.g. tones) sharing the same carrier frequency, a different signal transmitted from each antenna element. The composite calibration signal is received by the first repeater set to the calibration frequency and is looped back to the BTS. The BTS measures the composite looped back signal at the respective DSP 270 of each antenna apparatus receive chain. This permits determination of receive apparatus chain calibration factors at the calibration frequency.

Analogous to the earlier described method using a translating repeater, the BTS may also determine compensation factors for each transmit apparatus chain. The BTS

may separate the composite signal having the plurality of tones using DSP 270 received at any one of the antenna elements 210 into the plurality of individual signals having single tones which were originally transmitted by each of the antenna elements.

After adjustment for free space delay differences, the relative phase and amplitudes of each originally transmitted signal are compared to the amplitude and phase of the corresponding received signal to determine calibration factors for each antenna transmit apparatus chain. These calibration factors can be used to compensate for differences in the downlink path transfer function for each transmit apparatus chain at the calibration frequency.

Calibration factors for the various transmit apparatus chains and receive apparatus chains can be used to compensate for the signal shift differences at the first calibration frequency. The BTS steps to the next calibration frequency. BTS 200 can signal a second translating repeater set itself to a second calibration frequency and to go into a loopback mode. The above process can be repeated at the second calibration frequency. Calibration information is saved for each frequency and can be used to compensate for the transmit and receive apparatus chain propagation differences when call is assigned to the corresponding frequency.

Using Idle Frames of dedicated Control Channels (DCCH) and Stealing Random Access Channels to Support Calibration of a GSM Wireless Adaptive Array Antenna Using a Translating Wireless Repeater

Calibration of the various transmit and receive array chains may be performed in P1000803.DOC

a manner which does not impact the traffic capacity of the cellular system. In a first method, calibration may be performed without impacting system traffic capacity. Idle time slots of frames normally allocated for Standalone Dedicated Control Channels (SDCCH) on the downlink and idle Random Access Channels (RACH) on the uplink may be used to calibrate a GSM BTS having an adaptive antenna array using a remote device, such as a translating repeater. The invention uses a translating repeater with loopback capabilities as part of the calibration process.

A problem with using a translating repeater with loopback for calibration is that two traffic channels which may otherwise support cellular traffic may be occupied during calibration. In GSM systems, the uplink and downlink channels in systems having 8 time slots are offset by 3 time slots (time slots also referred to as burst periods). In GSM, from the BTS perspective, the uplink burst follows the downlink burst by 3 time slots. Alternatively, from the mobile's perspective, the downlink follows the uplink by three time slots. For example, from the mobile's perspective, if the downlink burst uses time slot 6, the corresponding uplink burst uses time slot 3. Consequently, if traffic time slots are used for antenna array calibration, antenna array calibration using a translating repeater with loopback in a GSM system would generally require two traffic channels be allocated for the calibration.

Various options are conceivable to avoid using otherwise active traffic channels. The calibration method could wait until two appropriately spaced time slots of a given carrier frequency become idle, but during busy times calibration could be significantly delayed and delay could result in degraded beamforming performance due to

component drift.

A more efficient calibration method is to use ("steal") a burst otherwise allocated for SDCCH on a downlink control channel for the BTS calibration signal and a RACH signal for the translating repeater uplink calibration signal. Time slots during the selected specific frames of the multiframe used align in time in the uplink and downlink direction.

SDCCH are stand-alone dedicated control channels included as part of the 51 frame control multiframe. When an SDCCH is configured on a time slot other than time slot 0, 8 SDCCHs are defined. When a mobile user accesses the cellular network using a RACH, the BTS 200 will assign the mobile user one of the 8 SDCCHs, unless the mobile is a GPRS mobile.

A GSM non-combined control carrier supports RACHs on the uplink on time slot 0 for all frames. Downlink SDCCH is specifically assigned to time slot 3 because the downlink SDCCH is desired to align in time with the uplink RACH which is fixed on time slot 0 in GSM systems. Time slot 0 is used exclusively for the uplink RACH. Other control channel configurations also allow the SDCCH to be multiplexed on time slot 0, but for purposes of this invention, this is not preferred because the downlink SDCCH would not align with the uplink RACH.

The last 3 frames of the 51 frame control multiframe configured to support SDCCHs are not used as they are intentionally left idle in GSM systems. Accordingly, in GSM systems, calibration signals can be transmitted by the BTS 200 during these idle frames, which are preferably assigned to time slot 3. This permits the translating repeater to transmit the frequency shifted calibration signal on time slot 0 normally

allocated to a RACH, stealing the RACH. Thus, the calibration is performed without utilizing time slots which can otherwise be used to support traffic.

The calibration signal cannot overlap into an adjacent time slot without being corrupted. Thus, the calibration signal should propagate from BTS 200 to the remote calibration unit and return so that the returned calibration signal does not overlap with an adjacent (later) timeslot. Therefore, it is preferable to use a short duration burst, such as a burst having the length of a RACH, because it is not known the length of time it will take for the transmitted calibration signal to return to the BTS 200. It is noted the calibration signal is not constrained to take on specific RACH characteristics, such as, modulation, channel coding, message content, etc.

There is a slight probability that a mobile attempting to access the system over the RACH will do so at the same time slot as the calibration signal is looped back by the translating repeater. However, in this situation, the system will behave the same as if the two mobiles attempted to simultaneously access the system. In this case, the mobile will re-attempt access at a later time. If the mobile corrupts the received looped back calibration signal such that it cannot be used, the system will simply reattempt calibration during the next multiframe.

Non-Intrusive Multicarrier Downlink Calibration for a Wireless Adaptive Antenna

Array Base Station Using a Remote Scanning Receiver

Downlink calibration may be performed by simultaneously transmitting different signals (e.g. different tones at a calibration frequency) from each BTS antenna element

and measuring the composite signal received by a remotely located scanning receiver. A remote scanning receiver can analyze a composite calibration signal over a band of frequencies to determine the magnitude and phase characteristics of each component signal, each signal traveling through a different transmit apparatus chain, after adjustment for respective free space delay differences.

The differences in the measured characteristics of each received component signal at the remote receiver is used to calculate calibration factors to compensate for the differences in the transmit apparatus chains associated with each array element. The invention allows downlink calibration at anytime without impacting the BTS' ability to process call traffic.

Applied to GSM systems, voice traffic channels are transmitted on 26 frame multiframe (26-multiframe). During any 26-multiframe, 24 frames are used for voice data, one frame is used for signaling between the base station and mobile (SACCH) and one frame (last frame) is intentionally left idle. During this idle frame, the base station can transmit a multi-tone calibration signal as previously described. A remote receiver can monitor the base station and synchronize itself to base station. Because it is synchronized, the remote receiver will know when the calibration signals will occur. The remote receiver can analyze the individual signals having distinct tones comprising the composite calibration signal received. After adjusting for the respective free space delay differences, the relative differences in the transfer functions of the transmit apparatus chains can be determined.

This information can be provided to the base station either on a wired or wireless

link to allow the base station to calculate calibration factors to compensate for the differences in each of its transmit apparatus chains. The scanning receiver can scan each frequency or a subset of frequencies used by the base station to monitor and analyze the calibration signals across the frequency band used by the base station. This calibration method allows periodic antenna array calibration with impacting any call processing capability of the base station by using periods of time during which a carrier frequency timeslot in a traffic multi-frame used by the base station is always idle.

Non-Intrusive Multicarrier Uplink Calibration For a Wireless Adaptive Array Base Station Using a Remote Calibration Transceiver

Uplink calibration may be performed by transmitting a calibration signal from a calibration transceiver or translating repeater positioned at a known location and measuring the calibration signal received by each antenna receive apparatus chain to determine the differences between the respective receive apparatus chain transfer functions. This information can be used to determine calibration factors to compensate for measured differences. The invention allows uplink calibration at anytime without impacting the base station's ability to process a call. For example, during an idle frame of the 26-multiframe, a remote calibration transceiver can transmit a calibration signal as previously described. To synchronize its timing, the calibration transceiver must include a receiver to receive periodic synchronization signals transmitted by the BTS.

One synchronized, the calibration transceiver can transmit a calibration signal to the BTS 200. The base station receives this calibration signal at each antenna receive

apparatus chain and its DSPs 270 can analyze each signal. This information can be compared and be used to determine respective receive apparatus chain calibration factors. The calibration transceiver can be configured to step its transmitter over each frequency or a subset of frequencies used by the BTS to determine calibration factors across the frequency band used by the BTS.

An intelligent Adaptive Array base Station Calibration

A calibration transceiver or translating repeater with loopback capabilities may be used as previously described. The previously described inventions required the calibration transceiver or translating repeater to be pre-programmed to operate at certain predetermined calibration frequencies.

The BTS can provide wireless information to the calibration transceiver or translating repeater to program it with the desired calibration frequency or frequencies, rather than relying on pre-programming. The calibration transceiver may be co-located with a BTS 200, but primarily used calibrate adjacent base stations. Alternatively, the calibration transceiver can be actually used in the cellular system.

A BTS regularly transmits a "neighbor list" over a control channel that mobile users use to determine the frequencies to scan adjacent cells. Scanning the received signal strength (RSSI) of mobile users from transmissions originating from base stations in neighboring cells is used by cellular systems to assist in mobile assisted handovers. The co-located calibration transceiver or translating repeater could also receive and use the information provided by the BTS transmitted neighbor list to determine the list of

calibration frequencies.

In addition, in some systems such as GSM, operator defined information that is not required for the operation of a conventional wireless system can be transmitted. In GSM, specific "System Information" supports this function. Information that is broadcast on the BCCH is broadcast in groups called "System Information." There are currently 16 different System information messages that are currently defined in the GSM 04.08, Mobile layer 3 Interface Specification. Standard. System information can be used to broadcast to "intelligent" programmable calibration units the calibration frequencies to perform the antenna array calibration.

Using Paging to Determine the Location of GPRS Mobiles for Beamforming of an Adaptive Antenna Array

Paging can be used to periodically update the location of GPRS Mobiles for a beamforming adaptive antenna array. In order to direct antenna beams and nulls to mobile users, mobiles must transmit a signal so that the BTS can continuously update the position of each mobile user. General packet radio service (GPRS) is used for applications such as e-mail and web browsing within cellular radio systems. GPRS and GSM can be simultaneously by the same base station or a base station can be configured to support either GPRS or GSM. GPRS uses the same multiframe structure as GSM for control channels. However, depending on the system configuration, different frames of the multiframe may be used for different types of GPRS or GSM control or traffic channels. GPRS and GSM may even share control channels.

Due to common GPRS applications, there is often significant periods of time between transmissions from a given mobile user. This can result in transmission gaps of several hours or more. Consequently, a mobile user can move a significant distance so that it is may no longer in the main antenna beam (or within the same cell) during the next transmission. Likewise, the interference environment can change significantly between transmissions, particularly over relatively long periods of time. To ensure the mobile periodically transmits to the BTS so that the BTS can determine the location mobile users and assess the interference environment, the BTS can periodically page mobiles that have not been active within a predetermined time frame. The transmitted paging signal will cause the mobile user to transmit in response to the page. The mobile's transmission permits the BTS to identify the location of the mobile, assess the interference environment and redirect its adaptive antenna beam accordingly.

While the inventions have been described with reference to the exemplary embodiments thereof, those skilled in the art will be able to make various modifications to the described embodiments of the invention without departing from the true spirit and scope of the invention.

